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Implications of Neutron Decoupling in Short Gamma Ray Bursts

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ABSTRACT

Roughly half of the observed gamma-ray bursts (GRBs) may arise from the shocking of an ultra-relativistic shell of protons with the interstellar medium (ISM). Any neutrons originally present in the GRB fireball may, depending on the characteristics of the central engine, dynamically decouple as the fireball accelerates. This leads to outflow consisting of separate fast proton and slow neutron components. We derive detailed implications of neutron decoupling for the observed lightcurves of short bursts. We show that the collision of a neutron decayed shell with a decelerating outer shell is expected to result in an observable second peak in the GRB lightcurve. There may be substantial optical emission associated with such an event, so the upcoming Swift satellite may be able to place constraints on models for short bursts. We also discuss interesting inferences about central engine characteristics allowed by existing BATSE data and a consideration of neutron decoupling.

Subject headings: Stars: Neutron — Gamma-rays: Bursts — Neutrinos

1. Introduction

GRB emission is widely thought to arise from the synchrotron cooling of electrons shock-heated in collisions involving ultra-relativistic shell(s) of particles. The collisions generating the shocks may be between two adjacent shells of ejecta (the "internal shock" scenario (Narayan, Paczynski, & Piran 1992; Rees & Meszaros 1994), or between an ultra-relativistic shell and the ISM (the "external shock" scenario (Meszaros & Rees 1993)). It has been argued that long complex bursts are most naturally explained by internal shocks Sari & Piran (1997) (see, however, Dermer & Mitman (1999)). Short, simple bursts, on the other hand, are well explained by external shocks onto a homogeneous ISM. In both scenarios, some compact, as of yet unidentified central engine must give rise to the ultra-relativistic flow. Leading models for the central engine include collapsars (MacFadyen & Woosley 1999), and the coalescence of a neutron star with another compact object (Eichler et. al. 1989).

It is a principal aim of GRB researchers to determine the nature of the central engine. In this work we show that, within the context of the external shock model for short bursts due to radiation-driven fireballs, existing BATSE and upcoming HETE-II, Swift, and Glast data on GRB lightcurves can be used make new and interesting inferences about GRB central engine parameters. In particular, we argue that the observed properties of short bursts may be used to differentiate between central engines emitting neutron rich ejecta, such as neutron star mergers, and central engines emitting neutron poor ejecta. This is interesting because neutron star mergers are at present a favored candidate for producing the timescales seen in the short class of GRBs. If, indeed short bursts arise from a different class of central engines than long bursts, and do not give rise to afterglows Kehoe et al. (2001); Hurley et al. (2001) then the results presented here may allow unique insights into the nature of these events.

The new inferences we discuss are obtained by considering the dynamics of the neutron component of the fireball. The basic idea is that if strong neutron-proton scatterings become ineffective at coupling neutrons to an accelerating radiation-driven gas, then these neutrons will be left behind with a smaller average Lorentz factor than the strongly Coulomb-coupled protons in the gas (Derishev, Kocharovsky, & Kocharovsky 1999b; Fuller, Pruet, & Abazajian 2000; Bahcall & Meszaros 2000). When this "neutron decoupling" occurs, the final fireball flow consists of two separate components: a fast proton shell and a slower neutron shell. When the neutrons in the slower shell decay they can shock with the decelerating proton component and give rise to a second, possibly distinct peak in the observed photon emission. This process is schematically illustrated in figure 1.

Roughly what is expected in this scenario is a first burst in the gamma-ray regime followed by a second burst which can peak in the x-ray, UV, or optical band. The first burst is a signature of the outer proton shell and the second a signature of the decayed neutron shell. Typically the delay between the bursts is a few milliseconds to several seconds, depending in detail on the neutron richness of the outflow and other central engine properties. The upcoming Swift [1] satellite, with a fast response time and x-ray and optical capabilities, may be ideally suited to look for evidence of neutron decoupling.

Observable effects of neutron decoupling for external shocks were first considered by Derishev, Kocharovsky, & Kocharovsky (1999a). Here we analyze in detail implications of this idea. In that work Derishev et al. also proposed the possibility of emission resulting from the decay of neutrons after arriving at the outer proton shock radius. As we show below, it is not clear if this case can be described in terms of the standard shocks discussed in connection with GRBs, and an analysis of the emission in this case has not been done. We therefore concentrate in this paper principally on the case where the neutrons decay before shocking with the outer shell, which is describable in terms of the standard theory of shocks.

In the next section we relate the observed timescales of short bursts to the necessary conditions for a decoupled neutron component to carry a substantial fraction of the fireball energy and decay before colliding with the outer shell. We also derive an interesting relation between neutron decoupling and the condition that the reverse shock in the outer shell is relativistic. In §3 we discuss the shock emission from the collision between the decoupled shell of decayed neutrons with the outer decelerating proton shell. This is similar to the work of Kumar & Piran (2000) who consider the implications of the late time emission of a slow baryon shell for the GRB afterglow. In §4 we use our results to draw some interesting conclusions about the properties of GRB central engines based on existing BATSE data. The last section is a summary and discussion of our results.

2. Short bursts due to external shocks and neutron decoupling

We first lay the groundwork for our discussion by presenting some results from the theory describing the shocking of an ultra-relativistic proton shell on the ISM. This problem has been considered by a number of authors and we refer the reader to Piran (1999) for a review.

Consider a relativistic shell expanding into the ISM. As the shell sweeps up the ISM it decelerates and two shocks form, a forward shock propagating into the ISM and a reverse shock propagating into the shell. The forward shock is generically relativistic. However, the character of the reverse shock and the details of

[1] http://swift.sonoma.edu

deceleration of the fireball depend on the dimensionless parameter

$$\xi = (l/\Delta)^{1/2}\gamma^{-4/3} \tag{1}$$

(Sari & Piran 1995). Here $l = (3E/4\pi n_{\rm ISM} m_p c^2)^{1/3}$ is the Sedov length, Δ is the width of the shell as measured in the observers rest frame (*i.e.* the frame in which the fireball is moving at γ), E is the total energy in the fireball, $n_{\rm ISM}$ is the number density of the surrounding ambient ISM, and m_p is the proton mass. If we write the energy of the shell in units of 10^{51}erg as E_{51}, the density of ISM in units of cm^{-3} as n_{ISM}, the Lorentz factor of the shell in units of 10^3 as γ_3, and the width of the shell in units of 10^7cm as Δ_7, then $\xi \approx 30\gamma_3^{-4/3}((E_{51}/n_{\rm ISM})^{1/3}\Delta_7{}^{-1})^{1/2}$. If $\xi \ll 1$ the reverse shock is relativistic and the energy conversion occurs principally in the reverse shock, while if $\xi \gg 1$ the reverse shock is Newtonian and energy conversion takes place principally in the forward shock. Interestingly, when $\xi \gtrsim 1$ initially, the shell spreads laterally as it expands and drives ξ to unity before shocking. When ξ is driven to unity the reverse shock becomes moderately relativistic, so that substantial energy conversion in the reverse shock also occurs in this case. We therefore focus on the case where $\xi \le 1$ at the time of substantial energy emission (see also Sari, Narayan, & Piran (1996)). Therefore, in the formulas that follow ξ is taken to be unity if initially $\xi > 1$.

The bulk of the observed emission occurs when the expanding shell slows substantially. This occurs when the energy imparted to the ISM is a sizable fraction of the initial energy in the shell. For $\xi \ll 1$ this corresponds to the point at which the reverse shock crosses the shell. In both cases ($\xi \ll 1$ and ξ driven to unity throuh spreading) the deceleration radius is written as (Meszaros & Rees 1993; Sari & Piran 1995)

$$r_{\rm dec} = l/\gamma^{2/3}\xi^{-1/2} \approx 5\cdot 10^{15}{\rm cm}(E_{51}/n_{\rm ISM})^{1/3}\gamma_3^{-2/3}\xi^{-1/2}, \tag{2}$$

which also serves to specify the dynamic timescale for the deceleration, $\sim r_{\rm dec}/c$. The observed duration of the burst is then

$$T_b \approx r_{\rm dec}/c\gamma_3(r_{\rm dec})^2\xi^{-3/2} = (0.2{\rm sec})\gamma_3^{-8/3}(E_{51}/n_{\rm ISM})^{1/3}\xi^{-2}. \tag{3}$$

The above equation is uncertain to within a factor of a few owing to the decrease in γ (deceleration) of the shell as it propagates. The factor of γ^2 in the denominator arises because of the relativistic motion of the shell towards the observer (Rees 1967). The factor of $\xi^{-3/2}$ arises because when the reverse shock is relativistic the Lorentz factor has decreased by a factor of $\xi^{-3/4}$ by the time the reverse shock crosses the shell. Note that T_b is equal to the width of the relativistic shell at $r_{\rm dec}$. For $\xi < 1$ lateral spreading of the shell is unimportant and T_b is just equal to the duration of emission from the central engine. With the above equations in hand we can discuss the implications of observed timescales of short bursts for neutron decoupling.

For both internal and external shocks substantial baryon Lorentz factors are required. A variety of mechanisms have been proposed to explain how the material acquires such a large kinetic energy. In a leading scenario, the fireball model, the baryons begin roughly at rest as part of a plasma with a large ratio of total energy to baryonic rest mass ($\eta \equiv E/M$). Thermal pressure then drives the acceleration of this plasma. Protons are strongly coupled to this high entropy gas via Thompson drag. Neutrons, however, are effectively only coupled via strong scatterings with protons and will eventually decouple. The condition that decoupling occurs before the end of the acceleration phase of the fireballs evolution is

$$\eta_3 > .3(E_{51}Y_e/R_6\tau_{\rm dur})^{1/4}. \tag{4}$$

Here $\eta_3 = \eta/10^3$, $Y_e = n_p/(n_n + n_p)$ is the net number of protons per baryon in the fireball, R_6 is the central engine radius in units of 10^6cm (this parameter determines the acceleration of the fireball), and $\tau_{\rm dur}$ is the duration of emission of the GRB central engine in seconds (so that $\Delta/c = \tau_{\rm dur}$). When Eq. 4 is satisfied the protons will keep accelerating while the neutrons are left behind. (If Eq. 4 is not satisfied the protons and neutrons still decouple, but have the same Lorentz factors because the fireball is no longer accelerating.) When Eq. 4 is satisfied and the neutrons dynamically decouple during the acceleration stage of the fireball's evolution, the fraction of initial energy going to the neutrons is

$$f_n \approx \frac{(1-Y_e)}{5}\left(\frac{Y_e E_{51}}{\eta_3^4 R_6 \tau_{\rm dur}}\right)^{1/3}, \tag{5}$$

and the final Lorentz factor of the protons and neutrons is given by

$$\gamma_{p,3} = \gamma_{n,3}\frac{(1-f_n)(1-Y_e)}{f_n Y_e} = \frac{\eta_3}{Y_e}(1-f_n). \tag{6}$$

(See Derishev, Kocharovsky, & Kocharovsky (1999b), Fuller, Pruet, & Abazajian (2000),or Bahcall & Meszaros (2000) for a detailed derivation of the above equations). In this equation $\gamma_{p,3}$ and $\gamma_{n,3}$ are, respectively, the final Lorentz factors of the proton and neutron shells in units of 10^3. Of course, if the neutrons initially present in the fireball are going to shock and lead to an observable photon signature they must first decay into protons. Even after they have decayed we will still refer to the slower inner shell as the "neutron" shell. We note that it was argued in Fuller, Pruet, & Abazajian (2000) that in fireballs with very low initial Y_e, the electron fraction will be driven to $Y_e \sim 0.05$ during neutron decoupling.

A useful relation, derivable from Eqs. 5 and 6, and valid when neutron decoupling occurs, is $\gamma_{p,3}^{4/3} = (1/5)(1-f_n)^{1/3}(\gamma_p/\gamma_n)(E_{51}/r_6\tau_{\rm dur})^{1/3}$. Using this relation and Eq. 1, note that there is a very interesting connection between the conditions in the neutron decoupled fireball and the initial value of the parameter ξ,

$$\xi = 3\frac{\gamma_n}{\gamma_p}\left(\frac{r_6^2}{\tau_{\rm dur} n_{\rm ISM} E_{51}(1-f_n)}\right)^{1/6}. \tag{7}$$

This implies that for a given ξ, neutron decoupling occurs in the progenitor fireball unless $n_{\rm ISM}E_{51}\tau_{\rm dur}Y_e/r_6^2 > (3)^6\xi^{-6}$. Therefore, *a strongly relativistic reverse shock ($\xi \ll 1$) implies that neutron decoupling has occurred in the progenitor fireball for essentially all reasonable fireball parameters.*

We are interested in the conditions under which a slow neutron shell decays and shocks with the outer proton shell. In order for this to occur, and in order for observable emission to result, the following conditions must be met: i) neutron decoupling occurs and leads to a final ratio of proton to neutron Lorentz factors of $\gamma_{p,3}/\gamma_{n,3} > \alpha$. Here α determines the strength of neutron decoupling and is chosen so that the emission from the two peaks is distinguishable. ii) the fraction of energy going to the neutrons is non-negligible (for definiteness we impose $f_n > 0.2$), and iii) the neutrons decay before colliding and shocking with the outer decelerating shell. We denote with a subscript p properties of the observed emission from the (faster) proton shell (so that $T_{b,p}$ is the observed duration of the first peak), and with a subscript n properties of the observed emission from the decayed neutron shell. When $\xi > 1$, the expression for the duration of the emission from the proton shell can be written in the useful form

$$T_{b,p} = 5(1-f_n)^{-1/3}\left(\frac{\gamma_n}{\gamma_p}\right)^2\left(\frac{(r_6\tau_{\rm dur})^2}{E_{51}n_{\rm ISM}}\right)^{1/3} \tag{8}$$

Eq. 8 allows us to relate the observed proton shell burst duration to the condition that the neutrons strongly decouple and carry a substantial fraction of the fireball energy (conditions (i) and (ii) above). Noting that $f_n = (1-Y_e)/(1+(\gamma_p/\gamma_n - 1)Y_e)$ we see that $\gamma_p/\gamma_n > \alpha$ and $f_n > 0.2$ when

$$\frac{5}{16}\left(\frac{Y_e}{1-Y_e}\right)^2 < T_{b,p}\left(\frac{E_{51}n_{\rm ISM}}{(r_6\tau_{\rm dur})}\right)^{1/3} < 5\alpha^{-2}\left(\frac{1+(\alpha-1)Y_e}{\alpha Y_e}\right)^{1/3}. \tag{9}$$

For given central engine parameters this range is large if Y_e is small, and vice versa. This is because when Y_e is small (*i.e.* the fireball material is neutron rich) γ_p/γ_n can be large while still leaving a substantial portion of the energy in the neutron component. Eq. 9 only applies for $\xi > 1$ initially and driven to unity through spreading. Note that when $\xi < 1$, $T_{b,p} = \tau_{\rm dur}$, and while condition (i) is easily satisfied, it is not possible to express condition (ii) in terms of observables. This is because the burst duration has no relation to γ_p/γ_n when $\xi < 1$.

In order to determine the properties of the burst arising from the neutron shell and also to determine whether or not the neutrons decay before colliding with the outer shell we need to specify how the outer shell slows with time. This requires knowing whether the evolution of the outer shell is adiabatic or radiative. Adiabatic evolution refers to the case where the energy generated in shocks with the ISM is not radiated away (*i.e.* most of the post shock energy is not in the electrons), or is radiated away on a timescale slow compared to the dynamic time of the fireball. The evolution is radiative if all the energy generated in the shocks with the ISM is effectively instantaneously lost from the system. This occurs when the fraction of post-shock thermal energy is principally in the electrons ($\epsilon_e \sim 1$) and the electron energy is radiated away quickly.

A common assumption regarding the fraction of post-shock energy going to the electrons is that ϵ_e is in the range $0.1 - 0.3$, *i.e.* significantly less than unity. In this case the outer proton shell initially slows approximately adiabatically regardless of the cooling time for the electrons. Because a radiative evolution is not ruled out, and to bracket the range of possible behaviors, we will also note results for the radiative case where appropriate. The true behavior will be somewhere inbetween. We will see that the characteristic timescales of the burst from the neutron shell are not very sensitive to the choice of adiabatic or radiative evolution of the outer shell. The spectral characteristics of the burst from the neutron shell, on the other hand, are more sensitive to the conditions in the outer proton shell when the two shells collide.

For the case of a Newtonian reverse shock ($\xi \sim 1$), Katz & Piran (1997) give the following analytic approximation to describe the slowing of the shell:

$$\gamma_p(t) = \frac{\gamma_p(t=0)}{2}\left(\frac{r_{\rm dec}}{ct}\right)^{3/2}. \tag{10}$$

For radiative evolution the exponent 3/2 above becomes 3. The time t appearing in Eq. 10 above and also in Eqs. 11 below is the time as measured by an observer at rest with respect to the central engine.

For the case where the reverse shock is relativistic the evolution is more complicated. We follow Sari (1997) in describing the evolution of the proton shell by a broken power law.

$$\gamma_p(t) = \frac{\gamma_p(t=0)\xi^{3/4}}{2}\left(\frac{r_{\rm dec}}{ct}\right)^{1/2} \qquad \text{for } \xi^{3/2}r_{\rm dec} < r < r_{\rm dec} \tag{11}$$

$$\gamma_p(t) = \frac{\gamma_p(t=0)\xi^{3/4}}{2}\left(\frac{r_{\rm dec}}{ct}\right)^{3/2} \qquad \text{for } r > r_{\rm dec} \tag{12}$$

Again the exponent 3/2 describing the later evolution would be 3 for a radiative evolution. When the reverse shock is relativistic a collision between the neutron and proton shells could occur before $r = r_{\rm dec}$.

This requires $\gamma_p(t=0)\xi^{3/4} \ll \gamma_n$, which is difficult to satisfy unless $\tau_{\rm dur}$ is very large and which also implies that the emission from the proton and neutron shells would not be well separated. In what follows we therefore concentrate on the case where $\gamma_p(t=0)\xi^{3/4} \geq \gamma_n$. Note that when $\gamma_p(t=0)\xi^{3/4} \geq \gamma_n$, spreading is important for the neutron shell because $t_{\rm collide}/\gamma_n^2 > \tau_{\rm dur}$.

With the above prescription for the evolution of the proton shell the two shells collide when

$$(\gamma_p(t)/\gamma_n)^2 = 1/4 \tag{13}$$

independent of ξ and at a time

$$t_{\rm collide} \approx \left(\frac{\gamma_p \xi^{3/4}}{\gamma_n}\right)^{2/3} r_{\rm dec}/c. \tag{14}$$

The fraction of neutrons decaying by this time is $f_{\rm decay} \approx 2.5(E_{51}(1-f_n))^{-1/12} n_{\rm ISM}^{-1/3} (r_6\tau_{\rm dur})^{5/12}(\gamma_p/\gamma_n)^{5/12}$. The condition that $f_{\rm decay}$ is substantial ($f_{\rm decay} > 0.5$) is

$$r_6\tau_{\rm dur}(\gamma_p/\gamma_n) > 0.02 n_{\rm ISM}^{4/5}(E_{51}(1-f_n))^{1/5}. \tag{15}$$

This equation is interesting because the fraction of neutrons decaying depends so weakly on all of the fireball parameters except $r_6\tau_{\rm dur}$ and γ_p/γ_n. For comparison, we note that when the evolution of the outer shell is radiative rather than adiabatic the condition that $f_{\rm decay}$ is substantial becomes

$$r_6\tau_{\rm dur} > 0.04 \xi^{3/5} n_{\rm ISM}^{4/5}(E_{51}(1-f_n)\gamma_n/\gamma_p)^{1/5}. \tag{16}$$

In the next section we turn to a description of the emission resulting from the shocking of the slower inner "neutron" shell once it collides with the decelerating outer proton shell. First, though, we note that Derishev, Kocharovsky, & Kocharovsky (1999a) have suggested that observable emission may result from the case where the neutrons decay after colliding with the proton shell. A quantitative assessment of this suggestion is not possible within the context of the standard picture of one body impinging and shocking on another. To see this, note that as the neutrons travel and decay they will decay on top of some ISM rest mass. In a time dt as measured by an observer at rest in the central engine rest frame a fraction of energy $dE_{\rm n\to p} \sim E_n dt/(\tau_n\gamma_n)$ appears in the form of protons from neutron decay. In this same time dt, the neutron shell will sweep over an ISM rest mass of $d{\rm M}_{\rm ISM} = r^2 c\, dt\, r_{\rm dec}^{-3} E_p \gamma_p^{-2}\xi^{-3/2}$ (this is obtained by noting that the ISM rest mass within $r_{\rm dec}^3$ is $\gamma_p^{-2}\xi^{-3/2}E_p$). A description of the ensuing process as a sweeping up a small amount of material and then a shocking is only possible if $\gamma_n^2 d{\rm M}_{\rm ISM} \ll dE_{\rm n\to p}$, or equivalently if

$$\gamma_n \left(\frac{c\tau_n r^2}{r_{\rm dec}^3}\right)\left(\frac{\gamma_n}{\gamma_p}\right)^2 \xi^{-3/2} \ll 1 \tag{17}$$

Because $\tau_n c > r_{\rm dec}$ is the condition that neutrons haven't decayed by $r_{\rm dec}$, Eq. 17 is in general not satisfied. This does not preclude substantial, observable emission from other processes, for example plasma instabilities. Further study may provide interesting insights.

3. Emission from the "neutron" shell

When the conditions presented above are satisfied, neutrons in the inner shell decouple from the proton shell, carry an energy comparable to the energy in the proton shell, and decay by the time they collide with the outer proton shell. This collision occurs at approximately the time $t_{\rm collide}$ given above and will generate a forward and a reverse shock. The characteristics of these shocks and the resultant emission depend on the structure of the outer shell at the time of the collision. We will consider two limiting approximations to this structure.

In the first approximation that we consider, the outer shell is assumed to have relaxed to a Blandford-McKee self similar solution. Also, the outer shell is assumed to be hot (at least in the proton component), so that the enthalpy in the outer shell is much larger than the rest mass energy density. Kobayashi, Piran, and Sari (1997) studied numerically the evolution of external shocks and showed that the Blandford-Mckee self similar solution is a good approximation once the shock has reached a radius greater than $\sim 1.4 - 1.9 r_{\rm dec}$, with the exact number depending on whether or not the reverse shock is relativistic. Therefore, for reasonable fireball parameters the collision between the inner and outer shells may occur while the outer shell is still relaxing to the self similar solution. A numerical solution of the evolution of the inner and outer shells would be needed to obtain the expected lightcurves in this case.

The expected emission in this first aproximation has been worked out in detail by Kumar & Piran (2000) and we draw on their results. When the inner cold shell collides with the outer hot shell a weak forward shock results. The effect on the emission from the outer shell is a modest increase in the total luminosity and little change in the spectrum. The reverse shock propagating into the inner shell is strong and mildly relativistic. The characteristic frequency for the emission from the inner shell is

$$(h\nu_{syn})_{|\gamma_{e,min}} \approx 1{\rm keV}\gamma_{n,3}^{5/2}\epsilon_e^2\epsilon_b^{1/2}n_{\rm ISM}^{1/2}(E_p/E_n)^{3/2} \tag{18}$$

This expression should be taken as somewhat approximate because a numerical study of the evolution of the reverse shock propagating into the neutron shell is needed for an accurate determination of the characteristic frequency. The flux at the characteristic frequency is larger by a factor $\sim (\gamma_n E_p/E_n)^{5/3}$ than the flux from the outer shell at the same frequency (Kumar & Piran 2000). If the observed emission from the proton shell arose from the reverse shock in the proton shell (which might occur if the emission from the forward shock occurs at too high a frequency to be observed by BATSE), then the characteristic frequency in the first and second peaks is similar. If, on the other hand, the dominant emission in the first peak arose from the forward shock propagating into the ISM, the first peak will have a much higher average energy than the second peak. The future GLAST mission[2] may therefore provide useful insights into this problem.

The spectrum of emission from the inner shell depends on whether or not the typical post-shock electron cools within a dynamical timescale. The thermal Lorentz factor of an electron which just cools on a hydrodynamic timescale is given by $\gamma_{e,c} = 3m_e c/(4\sigma_{\rm T} U_B \gamma_n t_{\rm hyd}) \approx 3(E_p/E_n)(1/n_{\rm ISM}\gamma_{n,3}^3\epsilon_B t)$. Here U_B is the magnetic field energy density in the inner neutron shell, $\sigma_{\rm T}$ is the Thomson cross section, $t_{\rm hyd}$ is the observed hydrodynamic timescale for the shell (approximately $r/c\gamma_n^2$), and t is the observed time in seconds. Because the thermal Lorentz factor ($\gamma_{e,{\rm therm}}$) for the average electron in the post-shocked inner shell is typically of order a few hundred or higher, we see that $\gamma_{e,c} \lesssim \gamma_{e,{\rm therm}}$ during the first few seconds. This means that we may approximate the electrons as fast cooling. In this case the flux from the neutron shell is proportional to $\nu^{-p/2}$ for frequencies above the characteristic frequency . Here p is the power law index characterizing the electron distribution in the shock (typically $p \sim 2.4$). Even though the characteristic frequency for the inner shell is low, significant emission can occur in the tens to hundreds of keV range if the index of the power law characterizing the post-shock electron distribution is close to 2.

[2] http://glast.gsfc.nasa.gov

The second approximation we consider is the case where essentially all of the shock energy generated in the outer shell goes into the electrons and is radiated away rapidly. In this case the two shells collide when they are cold and the collision will generate comparable forward and reverse shocks. The emission will be similar to that described in the first approximation discussed above. However, the characteristic frequency from these shocks can be a factor of tens to hundreds larger in this case because of the larger relative Lorentz factor of the shells at the time of the collision and because of the smaller enthalpy of the outer shell at the time of collision.

Interestingly, the signature from a neutron decayed shell can be quite similar to what is expected for the case where, following internal shocks, a relativistic shell collides with the ISM (Sari and Piran 1999). For example, for GRB 970228 one might interpret the first peak as arising from the forward shock occurring when a fast proton shell collides with the ISM, and the second peak as arising from the collision of a neutron decayed shell with the outer shell.

When the neutron shell leads to an observable peak, this second peak will have a characteristic duration

$$T_{b,n} \approx t_{\rm collide}/{\gamma_n}^2 \approx T_{b,p} \left(\xi^{3/4}\gamma_p/\gamma_n\right)^{8/3} \tag{19}$$

and the second peak will be separated from the first peak by an observed time

$$\delta t \approx (T_{b,p})\,(\gamma_p \xi^{3/4}/\gamma_n)^2((\gamma_p \xi^{3/4}/\gamma_n)^{2/3} - 1). \tag{20}$$

Although the results for the cases where $\xi < 1$ and where $\xi > 1$ initially can be written in similar forms, there is an important difference between these two cases. In the newtonian reverse shock case (ξ is driven to unity through spreading), $T_{b,n}$ and δt have a relatively strong dependence on γ_p/γ_n. Therefore, for the newtonian case, one could have $\gamma_p/\gamma_n = 10$, for example, leading to a second peak separated from the first by more than 100 first peak durations. However, for $\xi < 1$, $\gamma_p \xi^{3/4}/\gamma_n \approx 2(\gamma_p/\gamma_n)^{1/4}(r_6^2/\tau_{\rm dur} n_{\rm ISM} E_{51}(1-f_n))^{1/8}$ and the dependence of $T_{b,n}$ and δt on γ_p/γ_n is weak.

4. Information about central engine parameters from observed lightcurves of short bursts

In this section we illustrate how the observed temporal characteristics of short, simple GRBs may be used to determine properties of the burster central engine. We emphasize again that we are supposing short bursts to arise from external shocks. We also assume that thermal pressure (a fireball), and not for example magnetic fields, drives the acceleration of the baryons. Both are debated assumptions.

There are two types of short bursts amenable to our analysis. The first class is the set of bursts with single peaks of emission; we show below how the absence of a second peak leads to interesting constraints. The second class is composed of bursts with two or more peaks. These bursts can be used to infer central engine properties by attributing a portion of the burst to a neutron decayed shell. This second method is attractive because in principle it places strong constraints on the central engine parameters and the electron fraction in the outflow. However, because many short bursts have structures too complicated to be explained within the context of the neutron decoupling scenario (how does one get three peaks for example), this argument could only be convincing in a statistical sense.

We first examine the constraints on central engine parameters implied by single peaked events. A basic confounding issue with this analysis is the uncertainty in the parameter ξ, which describes the strength of reverse shock in the outer proton shell. If $\xi > 1$, then the absence of a second peak implies that one or both of Eqs. 9,15 were violated. The resultant constraints are illustrated in figure 1. If $\xi < 1$, it is in general easy to satisfy the neutron decoupling condition. However, as the burst duration is not related to γ_p/γ_n in this case, the absence of a second peak only gives weak constraints on the final Lorentz factor η of the fireball.

As a definite example, consider a neutron star merger model characterized by electron fraction $Y_e \sim 0.1$, $r_6 \approx 1$, and a duration of a few orbital periods ($\tau_{\rm dur} \sim 0.01s$). Now, all bursts with durations greater than $\tau_{\rm dur}$ (a few tens of msec) arise from fireballs with $\xi > 1$. If the neutron decay condition (Eq. 15) is satisfied, then one expects the presence of a second peak for all bursts with duration $\tau_{\rm dur} < T_{b,p}(E_{51}n_{\rm ISM})^{1/3} \leq 0.5s$. (Here we have taken $\alpha = 2$ as the criterion that the first and second peaks are distinguishable.) For this range of burst durations it is readily seen that the neutron decay condition (Eq. 15) is satisfied for $n_{\rm ISM} \sim 1$ when the evolution of the outer shell is approximately adiabatic. Therefore, a second peak in the GRB lightcurve for these events is expected.

We now consider short bursts with multiple peaks. A difficulty here is that the majority of bursts display complex time structure with many peaks. For these bursts an inhomogeneous ISM or some other mechanism must be invoked if they are to be explained by an external shock model. An analysis of implications of neutron decoupling for, *e.g.* an inhomogeneous ISM, would have to be done in order to look for correlations characteristic of neutron decoupling in these events. Here for simplicity we will focus on that subclass of bursts that display only two peaks. Of course, second peaks in these events may arise from the same mechanism that generates multiple peaks in more complicated bursts, and not from neutron decoupling.

The general features of a two peaked burst due to neutron decoupling are given in Eqs. 19 and 20. A first proton shell peak is followed by a longer neutron shell peak, with an inter-peak duration somewhat shorter than the neutron peak duration. When $\xi > 1$ initially and driven to unity through spreading, the ratio of first to second peak widths is a direct measure of γ_p/γ_n. In turn, γ_p/γ_n gives the relative energies of the two shells for a given Y_e. In particular, a large inferred γ_p/γ_n and comparable energies in the two peaks implies a low Y_e. A signature of low Y_e environments might be the presence of a population of bursts with $T_{b,n}/T_{b,p} \gtrsim 100$.

For $\xi < 1$ it is difficult to make interesting inferences about central engine parameters from two peaked bursts. This is because i) as noted above the neutron decoupling condition is in general satisfied for $\xi < 1$, ii) the requirement that f_n is non-negligible only leads to weak constraints on the final Lorentz factor η of the central engine, and iii) the neutron decay condition is principally sensitive to $\tau_{\rm dur}$ which is directly measured for $\xi < 1$. In addition, the neutron decay condition depends on ξ, which is not measured. Lastly, the weakness of the dependence of $T_{b,n}/T_{b,p}$ on the fireball parameters means that a ratio of first to second peak widths of order unity is compatible with a broad range of conditions.

To make the connection between the work presented here and observations of GRBs we display in figure 2 a plot of $\delta t/T_{b,p}$ versus $T_{b,n}/T_{b,p}$ for a sample of bursts that display only two peaks in BATSE energy channel 2. A proper analysis of these bursts would take into consideration the fact that a burst which displays only two peaks in a given energy channel may have more or fewer peaks in different energy channels. The fits we use were done by Andrew Lee (Lee, Bloom, & Petrosian 2000a,b). Peaks are described by a function of the form $I(t) = A\exp(-|(t - t_{\rm max})/\sigma_{r,d}|^{\nu})$. Here $I(t)$ is the observed intensity, $t_{\rm max}$ is the time at which the peak attains its maximum, σ_r and σ_d are the peak rise and decay times respectively, and ν characterizes the shape of the peak. We have followed Lee, Bloom, & Petrosian (2000b) in taking δt to be the difference between $t_{\rm max}$ for the two peaks, and in approximating each peak width as $T_b = (\sigma_r + \sigma_d)(-\ln(1/2))^{1/\nu}$.

A number of the bursts in figure 2 are compatible with the neutron decoupling scenario presented here. If one attributes the cluster of bursts with $\delta t/T_{b,p} \sim T_{b,n}/T_{b,p} \sim$ a few as arising from neutron decoupling, then either $\xi \sim 1$ and $\gamma_p/\gamma_n \sim$ a few, or $\xi < 1$ and γ_p/γ_n can be quite large if the outflowing material is neutron rich. Only the burst at $(\delta t/T_{b,p}, T_{b,n}/T_{b,p}) = (130, 192)$ might provide clear evidence for pronounced neutron decoupling and low Y_e. However, because ξ is proportional to γ_p/γ_n for a given set of central engine parameters, the absence of a population of bursts with large $T_{b,n}/T_{b,p}$ does not provide evidence against low Y_e central engines. A natural explanation for the absence of such bursts for low Y_e central engine models is that when γ_p/γ_n is large, the reverse shock occurring when the outer proton shell collides with the ISM is relativistic.

4.1. Neutron decoupling and precursors

Perhaps the most natural place to look for evidence of neutron decoupling is in those bursts identified to have precursors. Roughly, a precursor is a peak in the GRB lightcurve preceding the main emission and separated from the main emission by a period where the flux is dominated by the background. Koshut et. al. (1995) studied in detail 24 bursts ($\sim 3\%$ of their total sample) that satisfied their definition of having a precursor. Several of these 24 bursts are consistent with the neutron decoupling picture presented here and roughly half of them have $T_{b,n}/T_{b,p} \approx 10$. Koshut et. al. (1995) also find a significant correlation between $T_{b,n}$ and $T_{b,p}$, which is consistent with an explanation in terms of neutron decoupling. Most of the bursts they examine have several times more emission in the second peak than in the first (although there is a selection effect: they defined a precursor as an event having a smaller peak count rate than the main emission). Within the context of the neutron decoupling picture these precursor events might be interpreted as evidence for a large neutron fraction.

5. Conclusions

Neutrons play an interesting role in relativistic fireballs: the fraction of neutrons in the initial fireball may be a direct indication of weak physics or other properties of the GRB central engine (Pruet, Fuller, & Cardall 2001), the strong interaction cross section is just right for neutrons to dynamically decouple during the acceleration phase of a fireballs evolution, and the free neutron lifetime allows for the possibility of neutrons decaying and shocking with the outer proton shell when neutron decoupling occurs. Here we have explored in detail some implications of this last possibility.

Somewhat fortuitously, an observable photon signature of the neutron component is expected for a broad range of central engine parameters. This signature arises from the reverse shock propagating into the slower neutron decayed shell when it collides with the outer proton shell and is characterized by a second peak in the GRB lightcurve. The characteristic frequency of this second peak is typically in the few keV or lower range. We have derived the relation between the properties of these two peaks and the central engine parameters. The spectral and temporal correlations characteristic of this second peak may be looked for in statistical studies of GRB lightcurves. In principal, such studies could infer the electron fraction in the GRB progenitor fireball. Low electron fractions, which are thought to occur in neutron star-neutron star mergers, might evidence themselves in a population of two peaked bursts with an interpeak separation hundreds of times longer than the first peak duration. The population of bursts which contain precursors and which are characterized by stronger emission in the second peak than in the first may also be evidence for low electron fractions. Lastly, the upcoming Swift satellite offers a promising opportunity to search for evidence of neutron decoupling and infer central engine properties.

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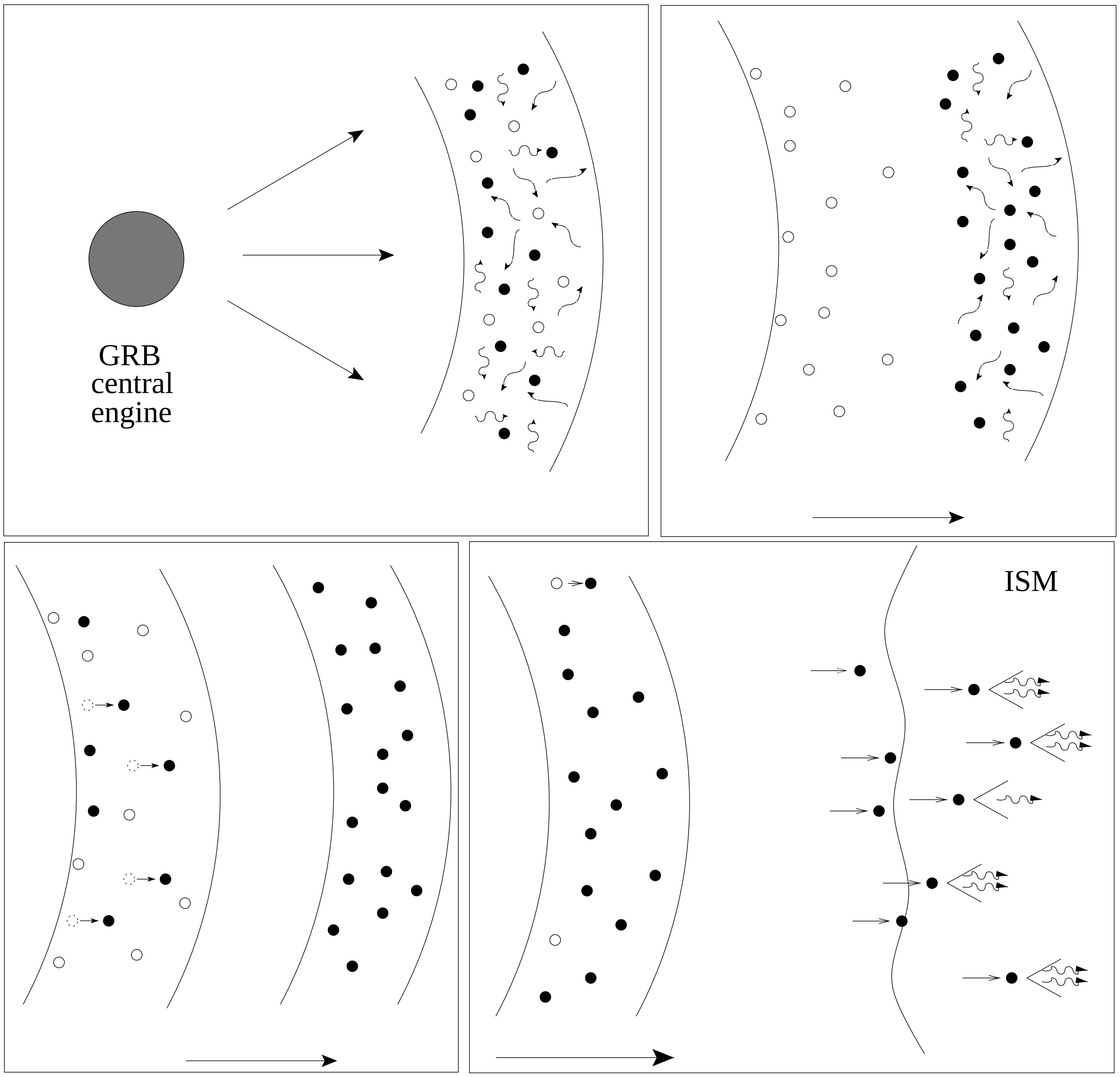

Fig. 1.— Illustration of the emission of a fireball by a compact central engine (upper left), neutron decoupling (upper right), neutron decay (lower left), and the shocking of the outer shell with the ISM and imminent shocking of the slower neutron decayed shell with the decelerating outer shell (lower right). The dark circles represent protons, the light circles neutrons, and the squiggly lines represent the radition driving the acceleration of the fireball.

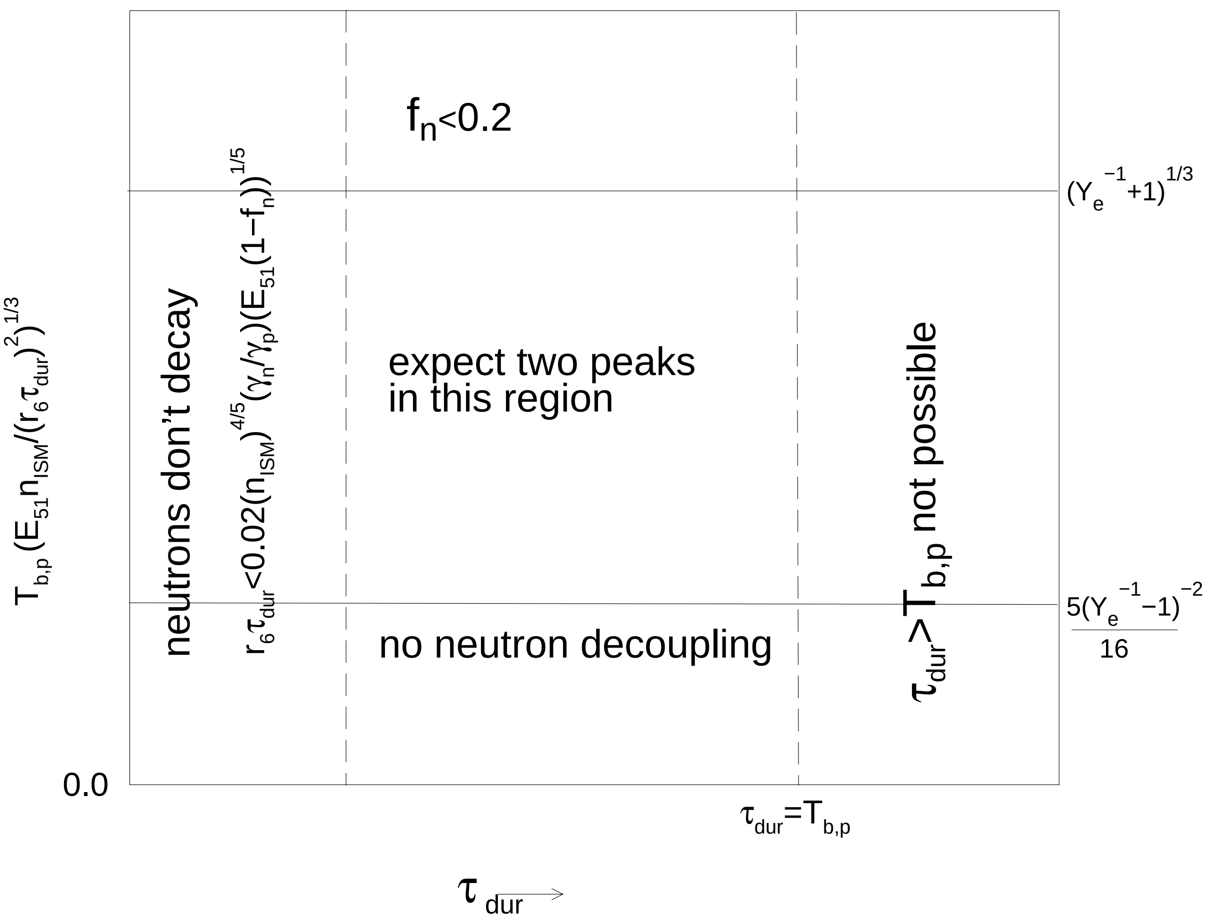

Fig. 2.— Illustration of the region of the parameter space for which an observable second peak arising from the shocking of a decayed neutron shell with a decelerating outer shell is or is not expected. The center box corresponds to the region for which one expects the presence of a second peak when $\xi > 1$ initially and driven to unity through spreading. In the region to the left of the central box the neutrons do not decay before colliding with the outer shell. Observable emission may result in this case but this possibility has not been studied in detail. The region above the central box corresponds to too little energy in the neutron component (neutron decoupling is too pronounced), while the region below the central box corresponds to no neutron decoupling. The region to the right of the central box is not allowed because the observed burst duration is always at least $\tau_{\rm dur}$.

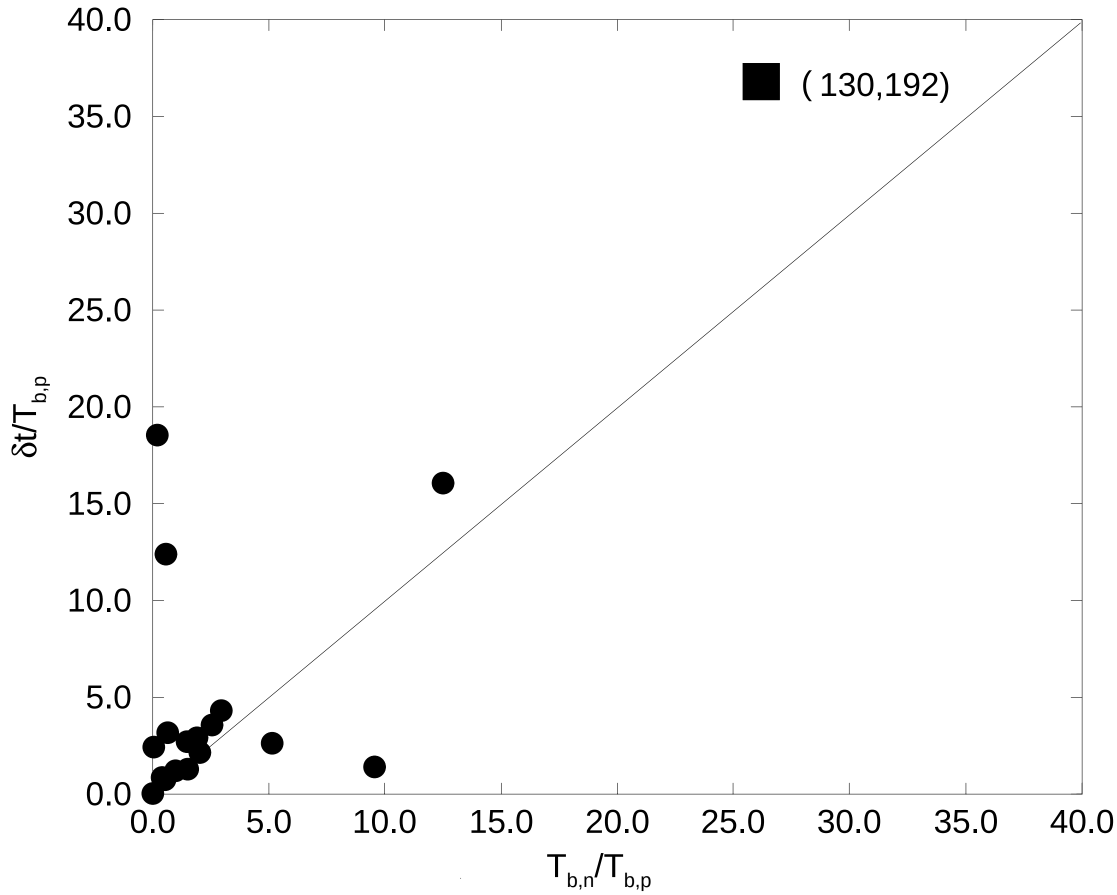

Fig. 3.— Plot of $\delta t/T_{b,p}$ versus $T_{b,n}/T_{b,p}$ for the bursts fit by Lee to have only two peaks in energy channel 2. The box in the upper right hand corner denotes a burst with $(\delta t/T_{b,p}, T_{b,n}/T_{b,p}) = (130, 192)$. Bursts falling near and to the right of the line are consistent with the neutron decoupling picture.